Chemical Engineering & Processing: Process Intensification 126 (2018) 23–37

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

A simplified strategy to reduce the desorbent consumption and equipment installed in a three-zone simulated moving bed process for the separation of glucose and fructose

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ARTICLE INFO

Keywords:
Desorbent consumption
Fructose
Glucose
Three-zone simulated moving bed (TZ-SMB)
Operational mode

ABSTRACT

The operating strategy of the three-zone simulated moving bed aiming for decreasing the desorbent consumption and the numbers of pump for the separation of glucose and fructose was proposed. Its principle was based on the port-relocation and port-closing/opening technique. The proposed strategy called PR-PCO-NFZIII was the re-arrangement of the outlet port such that the raffinate and extract were alternately collected with no flow in zone III during raffinate collecting period. The adsorption model was first verified with experiments in the three-zone simulated moving bed operational mode (TZ-SMB). Then the model was used in the simulation of PR-PCO-NFZIII. The calculated performance parameters of the TZ-SMB, port-relocation, and PR-PCO-NFZIII were compared. The results revealed that PR-PCO-NFZIII outperformed the TZ-SMB mode in terms of solvent consumption, reduced number of pumps, and pressure drop. With this simplified approach, the purities and productivities of both extract and raffinate product were not compromised with adjustable product concentration as a function of extract collecting time to suit the specific demand. Furthermore, with the suitable choice of partial collecting/discarding strategy, the extract and raffinate were greatly concentrated.

1. Introduction

The commercially known as high-fructose corn syrup (HFCS) comprises of fructose (with large proportion for high degree of sweetness) and glucose [1]. It is generally used as sweetener for sucrose substitute and is commonly found as ingredient in various foods and soft drinks [2]. The chemical reaction producing HFCS involves hydrolysis of starch into glucose followed by isomerization, converting glucose to fructose [3]. The process is carried out industrially using the integrated unit operation for separation and chemical reaction, known as simulated moving bed reactor (SMBR), which helps overcome the thermodynamic equilibrium limitation of the aforementioned reacting system by converting glucose and isolating fructose formed simultaneously [4–6]. The simulated moving bed (SMB) unit is also applied in various fields of research, e.g., petrochemical, pharmaceutical, and carbohydrate [7]. The principle of this system is based on the adsorption in a chromatographic column packed with solid adsorbent resin normally in calcium form for adsorption of sugar [8]. The apparatus consists of columns connected in series. The physical rotation of column in the direction of solid phase or the periodic shifting of all inlet and outlet ports in the direction of fluid flow simulate the counter-current movement of solid and fluid streams, which occurs in the true moving bed (TMB) [9–11]. This technique offers several advantages such as avoiding mechanical problem resulting from solid movement, constant product quality, enhanced productivity, reduced solvent consumption, and low separation cost [12,13].

One of the major factors affecting the design and operation of SMB unit is the number of valves and pumps installed in the system which is directly associated with construction and operating costs. Sufficient distribution of these equipment facilitates the flexibility and expandability of SMB, making it capable of adapting to a multiple SMB system and operational modes. However, a considerable number of valves and pumps also introduce extra- dead volume from increased transfer lines, which influences the separation efficiency [7,14]. Another important operating parameter is the solvent consumption which should be minimized without sacrificing the throughput [15]. In order to save the process cost while maintaining the high efficiency of SMB, the reduction in terms of the number of pumps and the desorbent utilization

Abbreviations: HFCS, high fructose corn syrup; SMB, simulated moving bed; SMBR, simulated moving bed reactor

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https://doi.org/10.1016/j.cep.2018.02.001
Received 2 October 2017; Received in revised form 31 January 2018; Accepted 2 February 2018
Available online 09 February 2018
0255-2701/

Nomenclature

a_i	Langmuir isotherm constant of component i
b_i	Langmuir isotherm constant of component i
$C_{i,k}$	Concentration of species i in liquid phase of zone k (g/L)
$C_{i,F}$	Sugar concentration of species i in the feed (g/L)
$D_{f,i}$	Diffusivity of species i (m^2/s)
D_{ax}	Axial dispersion coefficient (m^2/s)
H_i	Henry constant of species i
$k_{h,i}$	Mass-transfer coefficient (s^{-1}) of species i
L_c	Column length (m)
$m_{i,j}$	Isotherm constant of species i affected by the adsorption of species j
N_C	Number of column
$n_{i,j}$	Isotherm constant of species i affected by the adsorption of species j
$\bar{q}_i$	Average concentration of species i in adsorbed phase (g/L)
q_i^*	Adsorbed phase concentration which is in equilibrium with C_i (g/L)
Pe	Péclet number
Q_i	Volumetric flow rate in zone i (mL/min)
Q_D	Desorbent flow rate (mL/min)
Q_E	Extract flow rate (mL/min)
Q_F	Feed flow rate (mL/min)
Q_R	Raffinate flow rate (mL/min)
r_j	Molar ratio in the feed mixture
R_p	Adsorbent particle radius (m)
t_S	Switching time (min)
t_{S1}	Extract collecting time (min)
t_{S2}	Raffinate collecting time (min)
V_C	Column volume (L)
v	Interstitial velocity of fluid (m/s)

Greek Symbols

ε_b	External bed porosity
ε_p	Internal porosity of adsorbent particle
ε_T	Total bed porosityε
θ	Dimensionless time
χ	Dimensionless axial coordinate
θ_S	Fraction of extract collecting time
θ_{EC}	Fraction of extract partial collecting period
θ_{RD}	Fraction of raffinate partial discarding period

should be considered. To accomplish these tasks, a novel operation scheme of SMB must be developed.

Apart from classical mode, there is a considerable number of research shedding light on the operational modes of SMB to enhance the separation performance. For instance, the product purity and throughput can be improved by (i) rearrangement of the inlet and outlet port locations in order to use desorbent in a superior way [16,17], (ii) the product port closing/opening strategy conducted during a certain period of switching time for collecting the product only when the contaminant was completely isolated [18,19], (iii) the modification of feed pattern such as partial feeding which helps extend the distance between the front/rear edge of contaminant and the desired product port [20,21], (iv) the partial discard method which removes the small contaminated portion of product as waste (or as recycling substance combined with feed) at the beginning or at the end of the switching period for increasing purity, or discards the solvent for increasing the product concentration [22–24]. Different combinations of the aforementioned strategies were also selectively studied, e.g., the simultaneous application of partial feeding and port-location rearrangement to achieve the synergistic benefit resulting from the individual strategy [25], the utilization of partial feeding incorporated with partial closing of the product port for upgrading the SMB performance in terms of purity and throughput [26]. Among the strategies found in the literature, the operational modes employing the port-relocation and port closing/opening strategies appear to have a great potential to decrease the solvent consumption and the number of pumps installed in the system since the first one utilizes desorbent effectively, whereas the latter is capable of eliminating the extract/raffinate pump.

Therefore, the purpose of this work was to investigate the possible strategy, in terms of configuration arrangement, aiming for lowering the desorbent consumption and number of pumps employed in the application of three-zone simulated moving bed for glucose-fructose separation. The proposed strategy was based on the port-relocation and product-port closing/opening techniques. The mathematical model and their parameters accounting for the adsorption in a single chromatographic column developed from the previous work [27] were experimentally validated for the three-zone SMB operational mode. The model was then used in the simulation of the proposed strategies to investigate the performance of SMB in terms of major product concentration, purity, productivity, %recovery, and desorbent consumption. The performance parameters of those strategies were also compared with those of TZ-SMB and port-relocation modes.

2. Theory

2.1. Three-zone simulated moving bed operational strategy

2.1.1. Three-zone simulated moving bed mode

The three-zone simulated moving bed (TZ-SMB) operation chosen in this study is based on the well-known four-zone SMB but without zone IV, which is designed for the regeneration of desorbent fluid. The three-zone SMB configuration outperforms the traditional four-zone SMB in the aspects of system robustness, adsorbent utilization, and prevention of leakage due to high pressure [28,29]. In addition, since only three columns were utilized, some pipelines (connected between column and other equipment) as well as a recycle pump can be eliminated. This results in smaller dead volume compared to that of the conventional four-zone SMB process. The operation of three-zone SMB for one complete cycle (3 switching steps before returning to the original position) is depicted in Fig. 1a. Note that the number labeled on the column is the zone-number which changes from time to time depending on the positions of inlets and outlets while the columns are kept at rest. The task of zone I is for cleaning of solid adsorbent by desorption of adsorbed component; whereas zones II and III are separation zones, performing the adsorption/desorption duty of the more retained component (fructose) and the less retained component (glucose) [7]. According to Fig. 1a, the desorbent is fed at the entrance of zone I to wash all glucose and fructose retained in the bed, leaving the bottom of column as the extract product (rich in fructose). The extract stream then enters zone II, where fructose is further adsorbed, and glucose initially occupied in this zone starts to desorb. The feed mixture is introduced at the inlet of zone III, where the adsorption of both sugar components begins. In this zone, the majority of fructose is adsorbed, leaving glucose to exit zone III as the raffinate product (rich in glucose). For a successful separation, the majority of fructose should be confined in zone III. In addition, all sugar components occupied in zone I and glucose retained in zone II should be removed completely at the end of switching period. This operation is performed for a certain period called switching time, t_S. A periodic shifting of all inlet and outlet streams in the direction of fluid flow is conducted while keeping packing material at rest, resulting in the simulated movement of solid adsorbent in the